Cryogenic, X-band and Ka-Band InP HEMT Based LNAs for the Deep Space Network

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Abstract—Exploration of the Solar System with automated spacecraft that are more than ten astronomical units from earth requires very large antennae employing extremely sensitive receivers. A key figure of merit in the specification of the spacecraft-to-earth telecommunications link is the ratio of the antenna gain to operational noise temperature (G/Top) of the system. The Deep Space Network (DSN) receivers are cryogenic, low-noise amplifiers (LNAs) which address the need to maintain Top as low as technology permits.

Historically, the extra-ordinarily sensitive receive systems operated by the DSN have employed cryogenically cooled, ruby masers as the LNA. Recent advances in the development of indium phosphide (InP) based high electron mobility transistors (HEMTs) combined with cryogenic cooling have made this technology competitive with standard DSN maser technology. InP HEMT LNA modules are demonstrating noise temperatures less than ten times the quantum noise limit (10hf/k) from 1 to 100 GHz. To date, the lowest noise LNA modules developed for the DSN have demonstrated noise temperatures of under 4 K at 8.4 GHz and 11 K at 32 GHz. Front-end receiver packages employing these modules demonstrated operating system noise temperatures of 17 K at 8.4 GHz (on a 70m antenna at zenith) and 39.4 K at 32 GHz (on a 34m antenna at zenith).

The development and demonstration of cryogenic, InP HEMT based front-end amplifiers for the DSN requires accurate component and module characterization, and modeling from 1 to 100 GHz at physical temperatures down to and below 12 K, because of the broad band frequency response of InP HEMTs. The characterization and modeling begins with the HEMT chip, proceeds to the multi-stage HEMT LNA module, and culminates with the complete front-end cryogenic receiver package for the antenna.

This paper presents an overview of this development process with emphasis on comparison between modeled and measured results at 8.4 GHz. Results will be shown for devices, LNA modules, front-end receiver packages employing these modules, and antennae employing these packages.

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1. INTRODUCTION

A key figure of merit in the specification of the spacecraft-to-earth telecommunications link is G/Top, the ratio of the antenna gain to operational noise temperature of the system. The cryogenic, low-noise amplifiers (LNAs) used by the DSN address the need to maintain Top as low as technology permits. The development of cooled indium phosphide (InP) high electron mobility transistors (HEMTs) has enabled the demonstration of state-of-the-art LNA modules that are yielding noise temperatures less than ten times the quantum noise limit from 1 to 100 GHz (0.5 to 50 K). The state-of-the-art noise temperature of cryogenic, HEMT-based amplifiers has steadily improved since the invention of the HEMT. Notable examples at physical temperatures near 20 K are 5.5 K at 8.5 GHz in 1986 [1], 15 K at 43 GHz in 1993 [2], and 30 K at 102 GHz in 1999 [3].

The DSN is in the process of implementing this technology to meet its navigation, telemetry, radar and radio science needs at 8.4 and 32 GHz. To date, the lowest noise InP HEMT LNA modules developed for the DSN have demonstrated noise temperatures of under 4 K at 8.4 GHz and 11 K at 32 GHz. Front-end receiver packages employing these modules demonstrated operating system noise temperatures of 17 K at 8.4 GHz on a 70m Cassegrain antenna and 39.4 K at 32 GHz on a 34m beam wave-guide antenna both at zenith.

The noise, gain and maximum frequency of InP HEMTs at room temperature is steadily improving as the technology is being internationally developed and commercialized. Although device (commercial and research) noise temperatures continue to fall at ambient, there is no guarantee that an attendant improvement at cryogenic temperatures will be realized. To develop ultra-low noise microwave amplifiers for cryogenic applications, one must have a reliable source of state-of-the-art cryogenic devices and the capacity to accurately characterize them at the device or wafer level at cryogenic temperatures. The work described in this paper is based on a partnership among TRW, Inc., the Georgia Institute of Technology (GIT), and the Jet Propulsion Laboratory (JPL). TRW was responsible for device fabrication and optimization, GIT cryogenic device noise parameter characterization and JPL cryogenic device scattering parameter characterization, LNA module development and receiver implementation.

The development and demonstration of cryogenic, InP HEMT based front-end amplifiers for the DSN also requires accurate LNA component characterization and modeling from 1 to 100 GHz at physical temperatures down to and below 12 K. The characterization and modeling starts with the individual HEMT chip, RF and DC bias components, proceeds to the multi-stage HEMT LNA module, and culminates with the complete cryogenic front-end receiver package for the antenna.

Although the modeling and measurements are more challenging at 32 GHz, the LNA development process is the same for 32 GHz as it is for 8.4 GHz. This paper presents an overview of the LNA development process emphasizing measured and modeled results at 8.4 GHz. Results are shown for devices, LNA modules, front-end receiver packages with these modules and antennae system employing these packages.

2. Cryogenic Cooling

The DSN applies cryogenic cooling to a variety of low-noise microwave receivers such as mixers, masers, upconverters, parametric amplifiers and HEMT LNAs to significantly reduce thermal noise. To provide physical temperatures down to 4.2 K, commercially available helium closed-cycle refrigerators (CCRs) are usually employed. For temperatures below 4.2 K, a pumped, open cycle liquid helium bath, or hybrid CCR with a liquid bath is used. To obtain the lowest possible noise temperatures, as many of the input and output microwave components as feasible are cooled below ambient.

Cooling below 4.2 K can result in significant performance improvements for some front-end receivers, but not necessarily for HEMTs. Noise temperature measurements of GaAs HEMT LNA modules in liquid helium at frequencies of 8.4 and 32 GHz showed no gain improvement and less than 10% noise temperature improvement in cooling from 4.2 to 1.6 K [4]. Although comparable experiments have not been performed on InP based LNA modules, similar results are anticipated.

3. Noise Modeling

Due to the deleterious effects of Radio Frequency Interference (RFI), the need for calibration signals and to provide for redundant receive capability, additional passive microwave components (filters, isolators, adapters, couplers and polarizers) are required to implement an LNA module in a DSN anntenna. Since significant effort is devoted to minimizing the LNA module's noise temperature, an equivalent effort must be expended to minimize the noise temperature contribution of these components to meet the DSN low-noise receiver specifications.

A useful expression to determine the noise temperature contribution of passive two port networks can be derived from the noise temperature function of the noise wave matrix representation for a passive network [4]. When the network is placed at the input of an LNA the effective input noise temperature, T_e, of the cascaded pair is given by the following expression [5]:

$$T_e = \frac{[(L-1)+\Gamma_L{}^2]T_L + LT_{LNA}}{(1-\Gamma_L{}^2)}$$

where $L =$ loss ratio, $\Gamma_L =$ reflection coefficient, and $T_L =$ physical temperature of the passive network while $T_{LNA} =$ LNA module noise temperature. Hence, in order to minimize the noise temperature contribution of the passive network it must be well matched, low-loss and kept at the lowest physical temperature possible.

For purposes of circuit modeling and device characterization, any noisy linear active two port can be represented as a noiseless linear two port with the noise sources at the input and/or the output [7,8]. A convenient representation uses a series noise voltage (e_n) and a shunt noise current (i_n) source at the input [9]. This leads to four noise parameters (T_{min}= minimum noise temperature, R_{opt}= optimum source resistance, X_{opt}= optimum source reactance and R_n= equivalent noise resistance) that can be determined from the measurement of noise temperature as a function of the generator or source impedance. In this representation, the noise parameters are given by equivalent noise resistance, R_n, the noise conductance, g_n, and the correlation coefficient, r, as noted below

$$R_n = \frac{\langle |e_n|^2 \rangle}{4kT_0 B}, \quad g_n = \frac{\langle |i_n|^2 \rangle}{4kT_0 B}, \quad and\ r = \frac{\langle e_n i_n \rangle}{\sqrt{\langle e_n^2 \rangle \langle i_n^2 \rangle}}$$

where T_0 = 290 K, k is Boltzmann's constant, and B is the noise bandwidth.

The noise temperature (T_n) of the two port network is driven by a generator impedance Z_g is given by the expression

$$T_n = T_{min} + \frac{T_0 g_n}{R_g \left| Z_g - Z_{opt} \right|^2}$$

Where Z_{opt} is the optimal generator impedance that yields a minimum noise temperature and $Z_g = R_g + jX_g$ is the generator impedance. The relationship between the first set of noise parameters and those in the above expression is given by the following equations

$$X_{opt} = \frac{Im(C)}{g_n}, \quad R_{opt} = \sqrt{R_n / g_n - X_{opt}^2},$$

$$\text{and } T_{min} = 2T_0 \left[g_n R_{opt} + Re(C) \right]$$

where

$$C = r\sqrt{R_n g_n}$$

In principle, the above noise parameters (Z_{opt}, T_{min}, and R_n) for HEMT devices can be determined by measuring the noise temperature for at least four different known source impedances at a given frequency. However, to reduce errors more than four source impedance values are used. The noise parameters, along with the scattering parameters, can then be utilitized to derive a small signal noise model.

Although a number of semi-emperical as well as detailed numerical models are available, a very practical model is the one proposed by Pospieszalski [10]. This model uses simple circuit concepts that yield closed-form expressions for the noise parameters. This model introduces frequency-independent equivalent temperatures for the intrinsic gate resistance (T_g) and drain conductance (T_d). The equivalent noise model for the HEMT device is shown in Figure 1. The intrinsic elements are displayed using dashed lines while the extrinsic or parasitic elements (such as pad resistances, capacitances and inductances) use solid lines.

For low frequencies the intrinsic noise parameters are given by the following expressions

$$R_{opt} = \frac{\omega_t}{\omega} \sqrt{\frac{r_{gs} T_g}{g_{ds} T_d}}$$

where

$$\omega_t = \frac{g_m}{C_{gs}}$$

$$T_{min} = \frac{2\omega}{\omega_t} \sqrt{g_{ds} T_d r_{gs} T_g}$$

and

$$g_n = \frac{T_{min}}{2 R_{opt} T_0}$$

The utility of this model is that it predicts noise parameters for a broad frequency range from a single frequency noise-parameter measurement at a given temperature. It is also important to note that the minimum noise temperature is inversely proportional to g_m, the HEMT transconductance. Since the small signal voltage gain is directly proportional to g_m, the lowest noise devices will be the most difficult to stablilize.

4. InP HEMT Device

The HEMT is essentially a high-performance field effect transistor (FET) whose active region is a finely tuned multi-layered structure. The InP HEMTs developed by TRW for this work are grown by molecular beam epitaxy on 3 inch semi-insulating InP wafers. The cross-section of this device is shown in Figure 2. First, to inhibit impurity diffusion into the active region and to improve carrier confinement two buffer layers one of InAlAs and the other InP are grown on the semi-insulating InP wafer. Then the active undoped $In_{0.65}Ga_{0.35}As$ (65% indium concentration) layer is grown followed by another spacer layer of InAlAs to further improve carrier confinement and to reduce donor ion scattering. The donor Si atoms are added in a single atomic layer in the next undoped InAlAs Schottky layer. The last two layers are n-type InGaAs cap layer and a heavily doped InGaAs layer to provide ohmic contacts. The devices are then passivated with a thin SiN layer.

This layered structure produces a conduction band discontinuity that forms a triangular one-dimensional quantum well. Electrons from the InAlAs layer are attracted to and collect at the one-dimensional (vertical direction) conduction band minimum in the InGaAs side of the heterojunction, forming a two-dimensional electron gas in a plane normal to the vertical direction. The advantage of this structure is that conduction electrons experience minimal scattering events, since there are relatively few impurities in the undoped InGaAs layer, and thus approach intrinsic electron mobilities. As previously noted these high mobilities or g_m's in turn lead to extremely low noise and high gain devices.

5. Device Characterization and Modeling

A key step in the process of developing InP HEMT LNA modules is the accurate, broadband, cryogenic characterization and modeling of active and passive circuit components. From 0.05 to 50 GHz, device and component measurements covering room to cryogenic temperatures are made with a cryogenic, coplanar wave guide probe station. To enhance and extend component models up to 100 GHz, a

2 ½ dimensional electromagnetic simulator (Sonnet Software, Inc.) was used.

For the purposes of this exacting work two systems were developed, one at JPL and the other at GIT. The coplanar wave guide probes and the copper sample holder are contained within a vacuum vessel and connected with fine gauge copper welding cable to the 12 K stage of a Gifford-McMahon (GM) CCR. To provide both mechanical strength and thermal isolation, the microwave probes are mechanically connected with G10 fiberglass tubing to end plates that are mounted to multi-axis manipulators having 3 degrees of freedom and one degree of rotation. A metal bellows at both the input and output end plates allow probe movement and placement within the vacuum vessel. The dc bias and RF signal is applied through copper plated stainless steel semi-rigid coaxial cable.

In general, the JPL and GIT systems are quite similar with just two notable differences. Both systems can measure on-wafer s-parameters at both room and cryogenic temperatures from 0.05 to 50 GHz. The GIT sample holder can move relative to the probes and the station has noise parameter measurement capability from 2 to 26 GHz. The JPL sample holder is fixed relative to the probes and an impedance generator is being developed for the input probe that will provide noise parmaeter measurement capability from 30 to 34 GHz. A photograph of the JPL probe station is shown in Figure 3.

The HEMT circuit model used in for the LNA module design shown in Figure 1 includes the extrinsic elements.

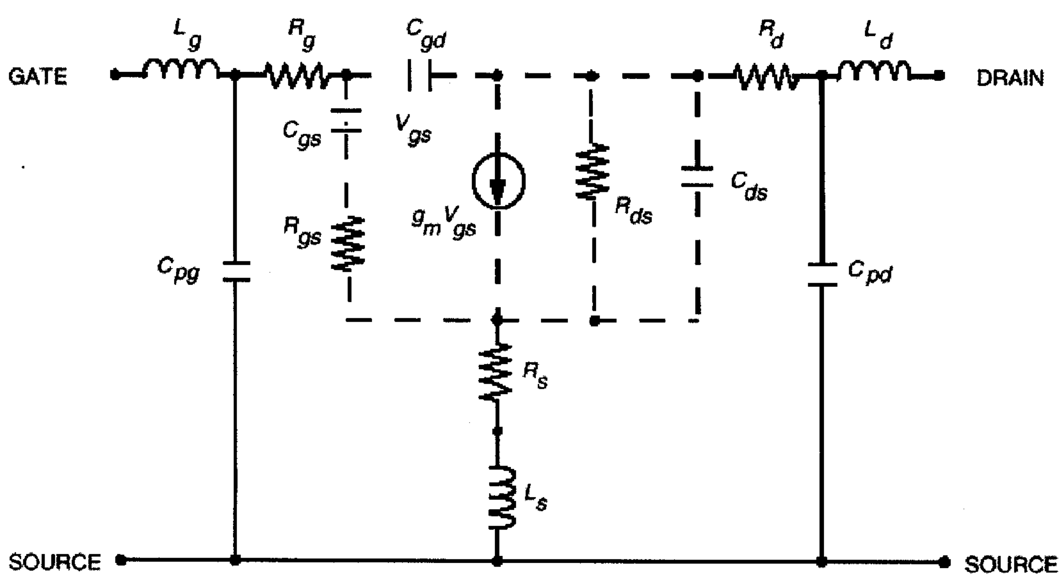


Figure 1. HEMT device equivalent circuit model

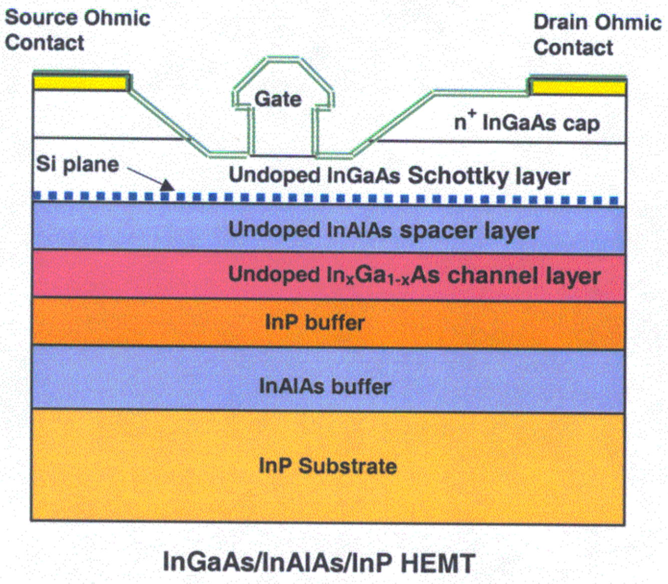


Figure 2. Cross-section of InP HEMT device

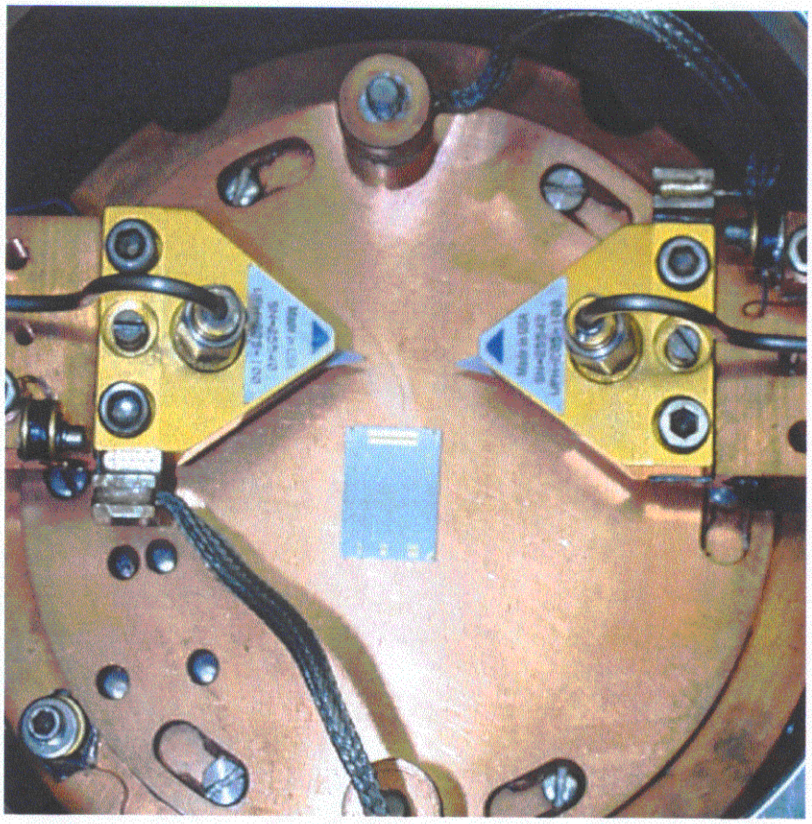
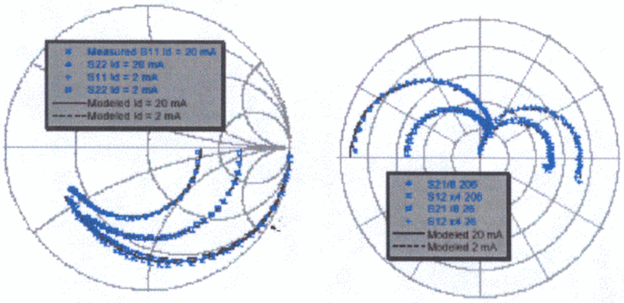


Figure 3. Photograph of the JPL cryogenic probe station

This widely used standard HEMT model [11] possesses physically realizable elements, is symmetric and sufficiently broadband for this work. The details regarding the scattering and noise parameter calibration procedures and measurements along with the circuit element extraction method are covered in previous articles [12, 13, and 14]. Figure 4 shows the agreement between the measured and modeled scattering parameters at 18 K at two different drain current values, 2 mA and 20 mA.



(a) (b)

Figure 4. Cryogenic measured and modeled s-parameters of 32 GHz HEMT at Ids=2 and 20 mA

From 1 to 40 GHz Sonnet was used to verify our cryogenic measurements and to refine and extend our user defined cryogenic models employed in MMICAD (Optotek, Ltd.) to 100 GHz. Although measurements to 40 GHz are sufficient for the 8.4 GHz LNA module modeling and design, it is inadequate for the 32 GHz LNA module modeling and design. The maximum frequency of operation, f_{max}, for the 32 GHz device approaches 150 GHz. Thus, at 32 GHz, especially in regards to stability, it is critical to have accurate component models up to 100 GHz. Figure 5 shows the measured and modeled response of a 16 pf bias circuit capacitor at both room and cryogenic temperatures.

6. LNA Modeling and Characterization

The design approach and fabrication process for both the 8.4 GHz and the 32 GHz LNA modules are essentially the same with some practical differences. At 8.4 GHz only three stages are needed, since there is sufficient gain per stage, while the 32 GHz module requires four. The 8.4 GHz module uses TRW InP HEMTs in the first two stages and a commercial PHEMT (pseudo-morphic HEMT) in the third, while the 32 GHz module uses TRW InP HEMTs in all four stages. Additionally, WR-28 wave guide input and outputs are used at 32 GHz instead of coaxial k-connectors to further reduce RF losses.

The LNA module design goal is to minimize the noise temperature at the DSN band of operation while at the same time maintaining unconditional stability both inside and outside the module's bandwidth. The 8.4 GHz LNA is designed to be unconditionally stable from 0 to 40 GHz, while the 32 GHz LNA is designed to be unconditionally stable from 0 to 100 GHz.

Since all of the devices used for the LNA designs are unstable, i.e. mu-factor > 1 [15], over their usable gain bandwidth, the first step is to stabilize the device at the LNA module band of operation without significantly increasing the device noise temperature. For example, for the 8.4 GHz LNA module design the first stage device is first stabilized near 10 GHz by a judicious choice of gate, drain, and source bond wire lengths. Next the device gate and drain bias networks are used to load the device and control the stability below 10 GHz and from 10 to 40 GHz, respectively. The rest of the stages are similarly optimized. The loaded, biased devices then serve as the fundamental circuit building block. A similar proceedure is used for the 32 GHz LNA module design. Figure 6 shows how the device bond wires and bias network affect and help control the device stability, while Figure 7 shows the trade-off, an associated increase in noise temperature for the 8.4 GHz first stage device.

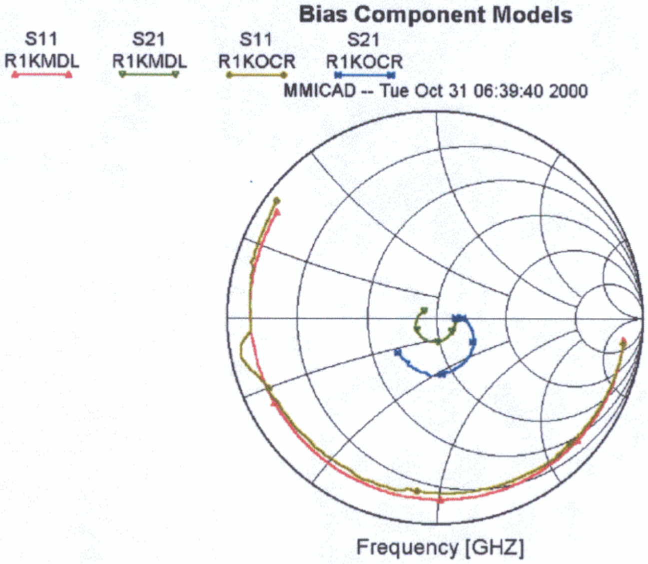


Figure 5. Measured and modeled 16 pF bias capacitor at 296 and 18 K

Then each of the stages is iteratively matched to its optimum source and load impedance. At 8.4 GHz the first and second stage are optimized for noise performance while the third stage is optimized for gain and output match. Following initial optimization, the LNA model is loaded at the input and the output with the string of passive microwave components, that will be implemented for field use, and the bond wire lengths re-optimized.

A photo of the 8.4 GHz LNA module is shown in Figure 8. The module carrier is gold-plated brass, the input, inter-stage and output matching circuits are etched on Cuflon and the dc blocking and bias circuitry use surface mount, thin film resistors and capacitors.

The completed LNA modules are then characterized in a cryogenic test-bed at a physical temperature of 12 K using the cold attenuator method [16]. A photo of the 32 GHz test-bed is shown in Figure 9. In this technique a 20dB attenuator connected to the LNA module input is cooled along with the module. The cooled attenuator serves as the cold noise source when the hot noise source, noise diode, is turned off and eliminates impedance match errors associated with the noise diode on-off states. The noise and gain are automatically measured using a commercial noise diode and noise figure meter. At 8.4 Ghz the gain measurement error is approximately +/- 0.1 dB and the error is +/- 0.3 K, while at 32 GHz the errors are about five times higher. Figure 10 shows the measured and modeled noise and gain performance of the 8.4 GHz LNA, while Figure 11 shows a similar plot for the 32 GHz LNA module. The module is subsequently cooled without the attenuator and the output monitored for oscillations or instabilities with a spectrum analyzer as the input impedance is varied.

7. Subsystem Measurements and Results

Following complete characterization, the LNA module is integrated and measured with the necessary filters, isolators, and adapters. This cascaded network is placed in a larger test-bed and characterized once again using the cold attenuator method described above. A photo of the cascaded LNA network is shown inside the test bed in Figure 12. Noise temperature and gain measurement results are shown in Figure 13.

Finally, the LNA module and components are integrated into the CCR package and characterized using the DSN's ambient load/cold sky method [17]. A photo of the LNA CCR package is shown in Figure 14. (Current systems use a CCR built by Sumitomo Heavy Industries Ltd. which provide 1.5 watts of cooling capacity at a physical temperature of 4.2 K.) This method uses the sky as the cold noise source and ambient load as the hot noise source placed over a calibrated feed horn [18] to determine the LNA CCR package noise temperature. Noise temperature measurements (RCP and LCP) of DSN LNA CCR Package are shown in Figure 15. These measurements are referenced to the room temperature wave guide input flange.

Once implemented in the field these front-end receivers demonstrated operating system noise temperatures of 17 K at 8.4 GHz on a 70m Cassegrain antenna and 39.4 K at 32 GHz on a 34m beam wave-guide antenna both at zenith [19]. (To date, three more 8.4 GHz and two 32 GHz comparable front-end receivers have been delivered to the DSN.) At 8.4 GHz this Top is within 1 K of the predicted value, while at 32 GHz it is within 2.5 K. This close agreement between predicted and measured performance is a testament to the measurement and modeling accuracy required to successfully develop these ultra-low noise cryogenic, InP HEMT based CCR receive systems.

8. Conclusion

The work reported here is the by-product of an on-going program at JPL to develop cryogenic InP HEMTs and MMICs for both ground-based and space borne radiometers and receivers. This work is thoroughly investigating the device parameters that will yield the best InP HEMTs. This study is investigating a variety of indium concentrations, dopant concentrations and profiles, spacer and buffer layer thickness and compostion, and device geometry variations (shorter length gates and/or multiple gates, sources, and drains). In summary, the device types successfully fabricated to date are of five different indium concentrations (53, 60, 65, 70 and 80%) with two different gate dimensions (0.1 and 0.07 microns) [20]. This study continues and has yielded the ultra-low noise HEMT shown in Figure 2 and reported in this paper.

In order for the noise temperature of a cryogenic, 32 GHz HEMT LNA module to drop to 3 K, the HEMT maximum frequency of operation, f_{max}, should exceed 500 GHz. The f_{max} of the InP device used for the 32 GHz modules was 150 GHz. The best TRW InP devices that are currently being tested have f_{max}'s of 250 to 300 GHz. TRW device research is aimed at pushing f_{max} beyond 300 GHz.

Although the emphasis of this article is technical, it must be pointed out that the partnership among JPL, GIT, and TRW is really the corner stone of this work. This partnership has been on going for several years and has provided the right technical mix to develop all of the key components required for the successful development of 8.4 and 32 GHz of state-of-the-art, ultra-low noise cryogenic, InP HEMT based CCR receive systems for the DSN. In summary, the key contributions of each of the partners were cryogenic, LNA module design and characterization (JPL), cryogenic, on-wafer noise parameter measurements and HEMT modeling (GIT), and state-of-the-art cryogenic, InP HEMTs (TRW).

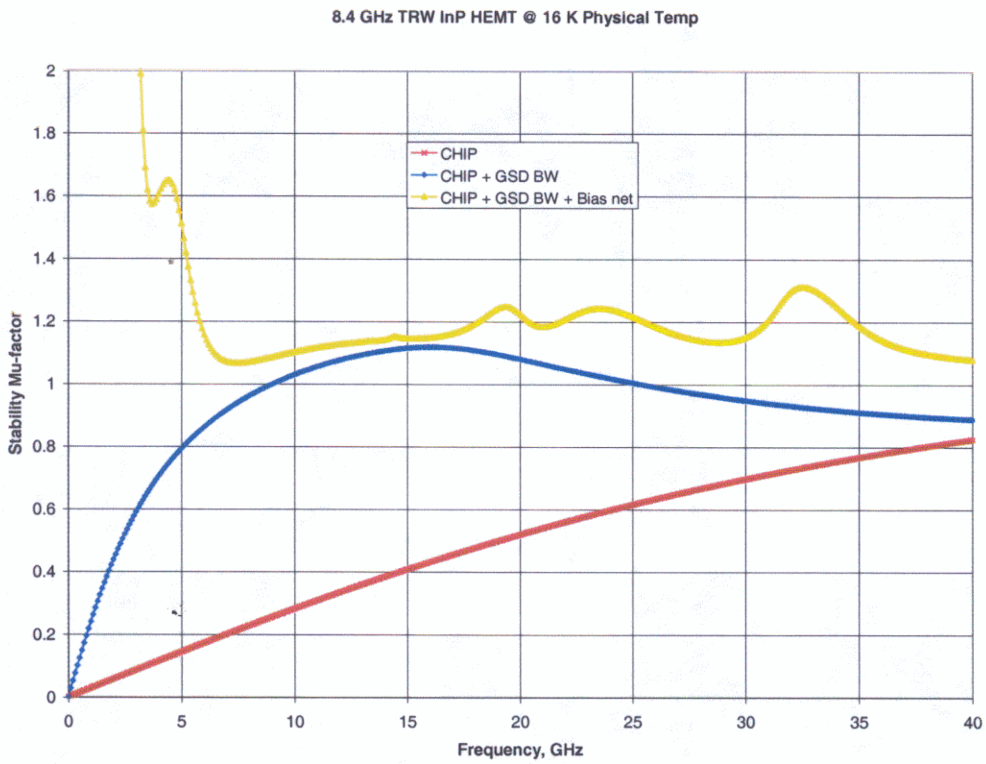


Figure 6. Bondwire and bias circuit stability (mu-factor) affects

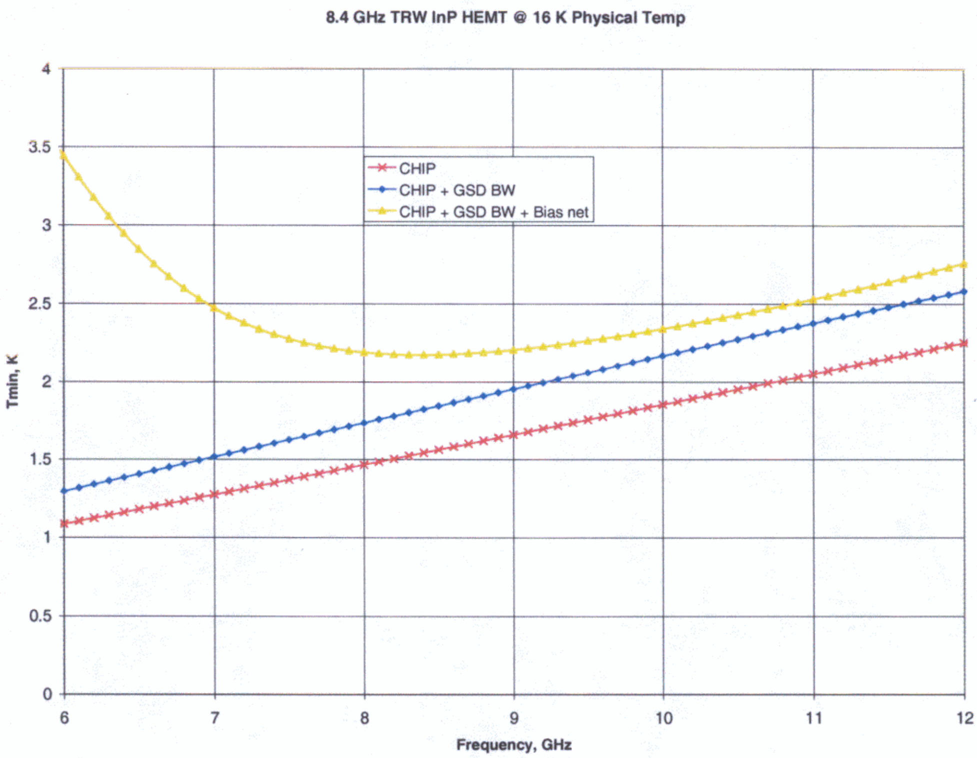


Figure 7. Bondwire and bias circuit minimum noise temperatue (Tmin) affects

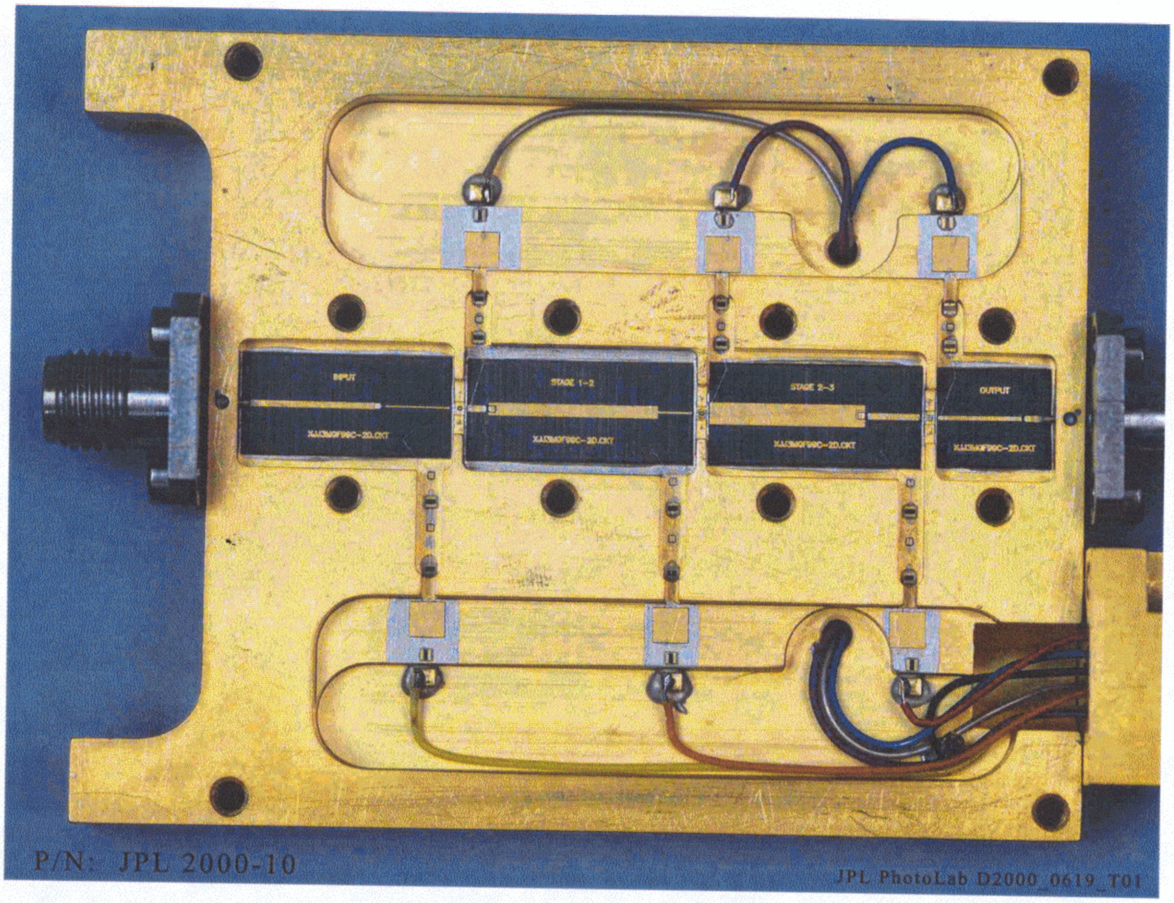


Figure 8. Photograph of three-stage 8.4 GHz InP LNA module

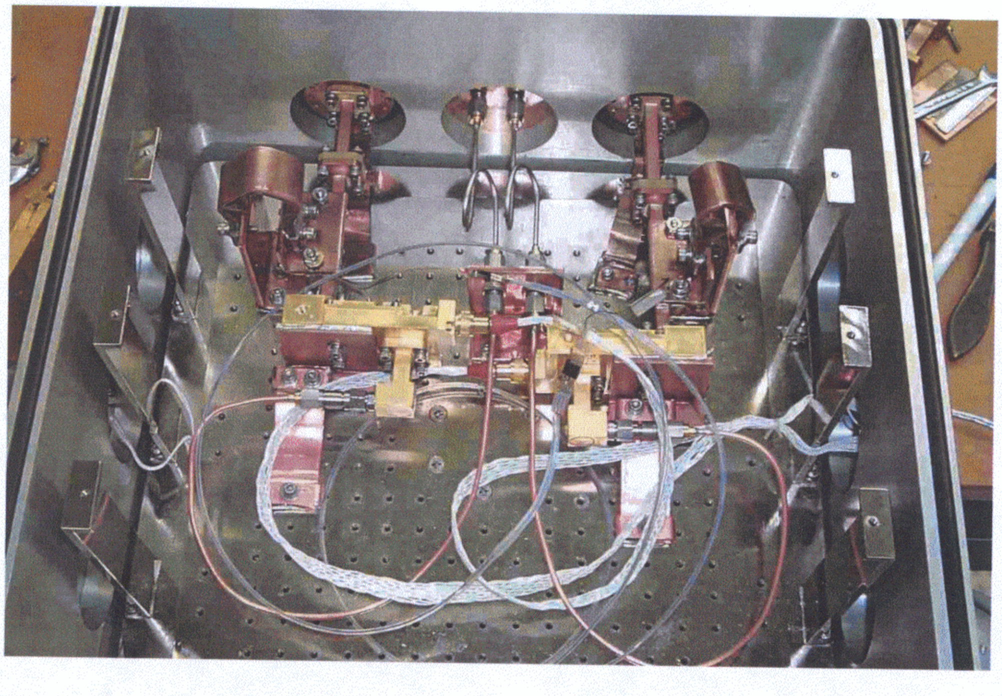


Figure 9. Photograph of the 32 GHz LNA cryogenic test-bed

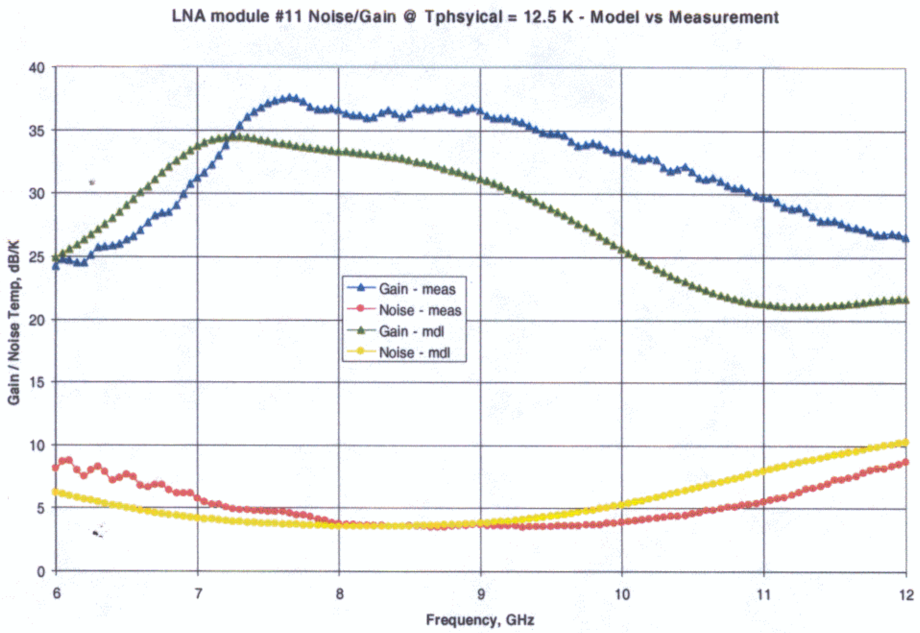


Figure 10. Measured and modeled noise and gain of 8.4 GHz LNA module

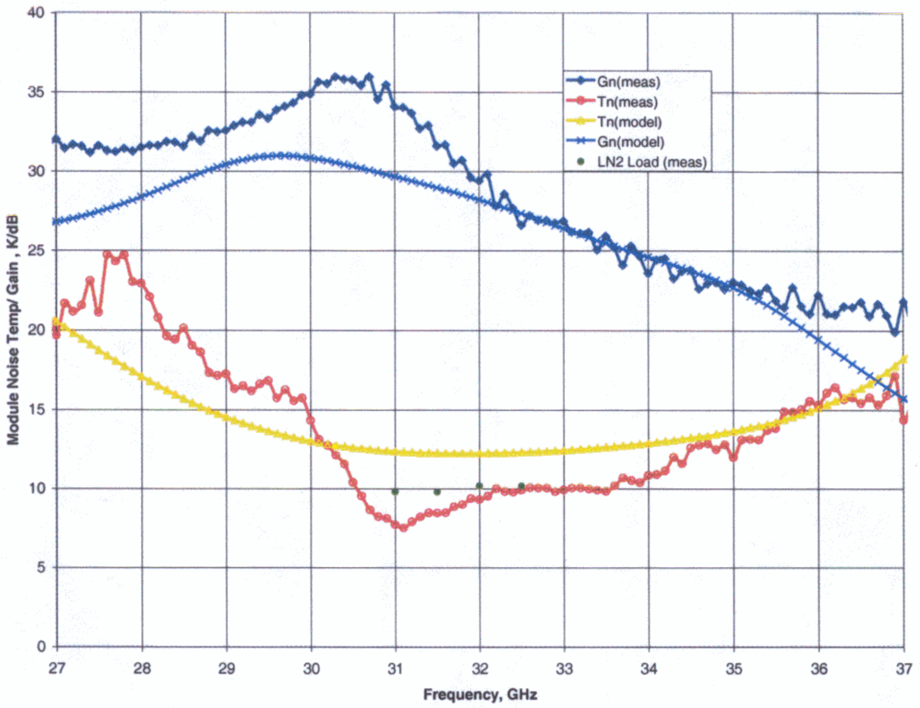


Figure 11. Measured and modeled noise temperature and gain of 32 GHz LNA module

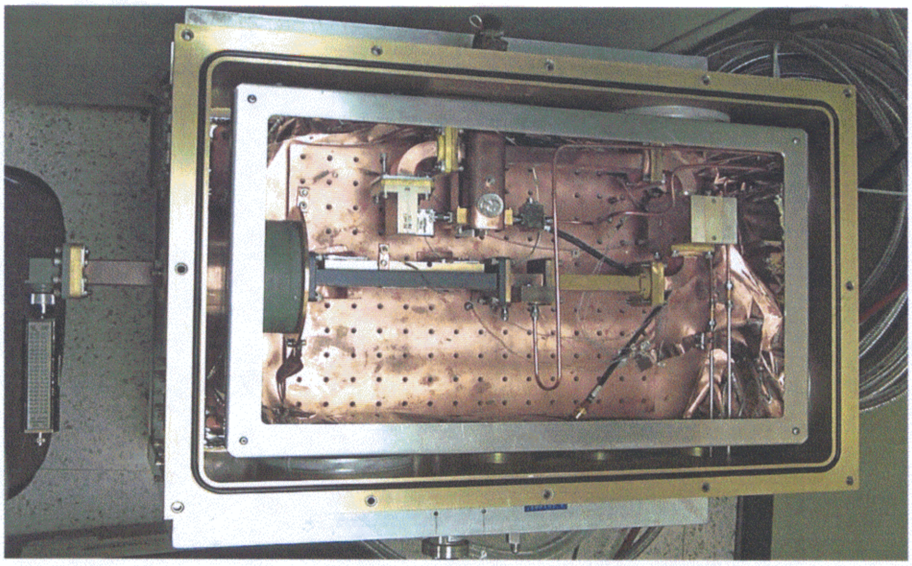


Figure 12. Photograph of the cascaded LNA assembly in test-bed

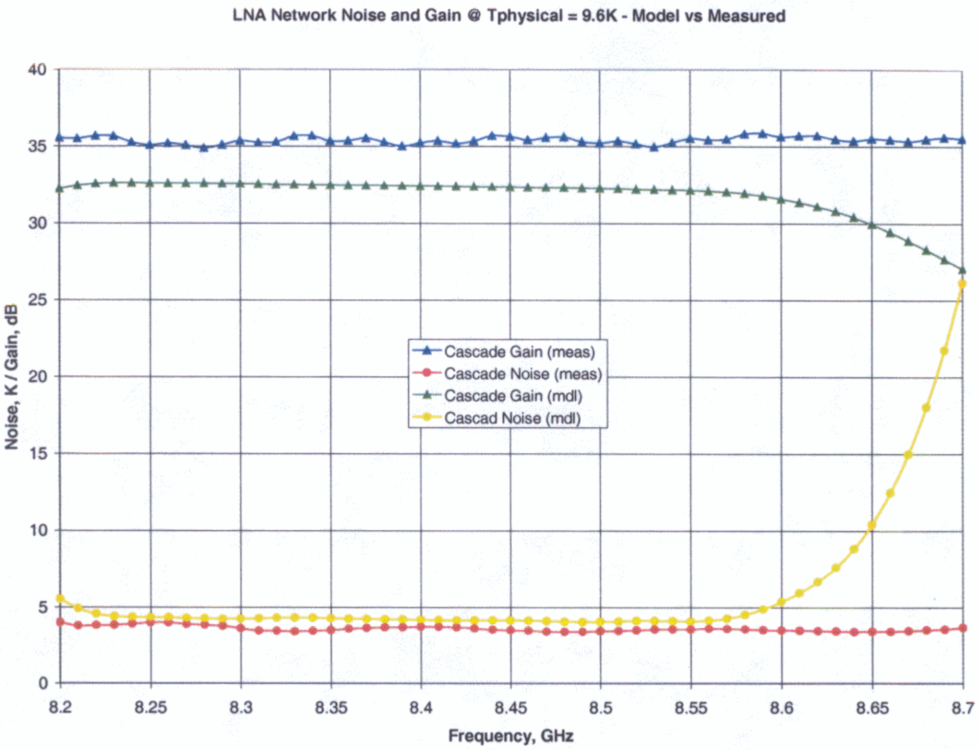


Figure 13. Cascaded LNA assembly noise and gain at 9 K

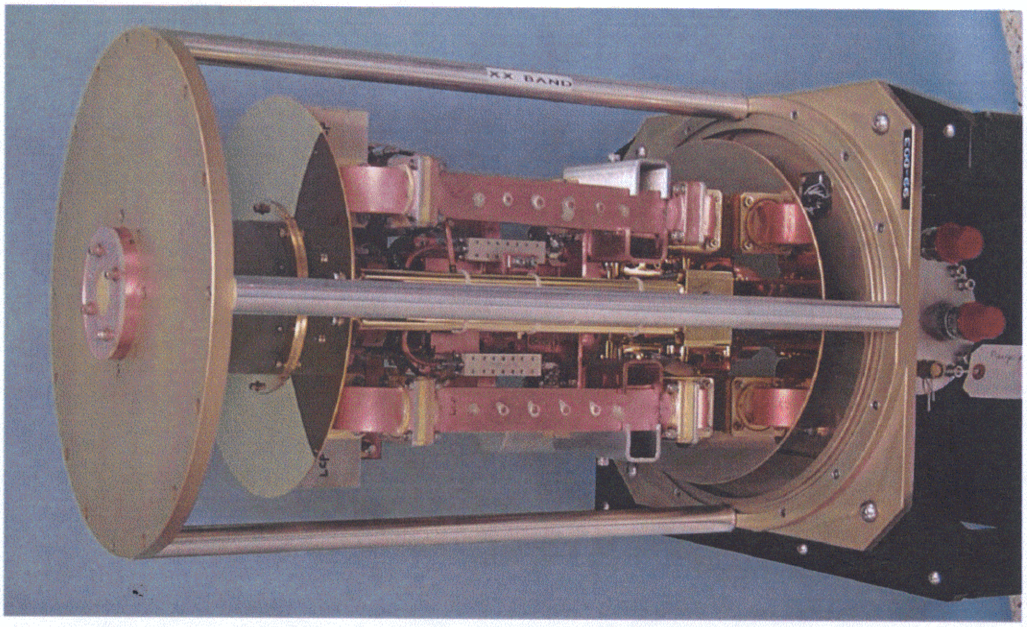


Figure 14. DSN Dual Channel InP HEMT/CCR LNA package

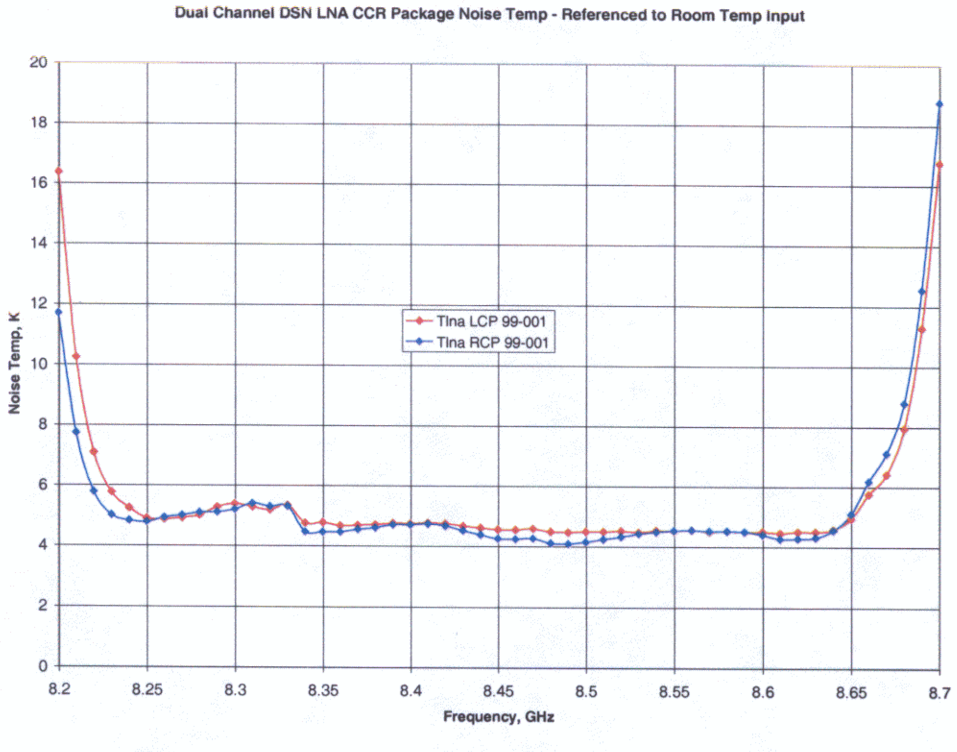


Figure 15. Measured noise temperature of DSN Dual Channel InP HEMT/CCR LNA package

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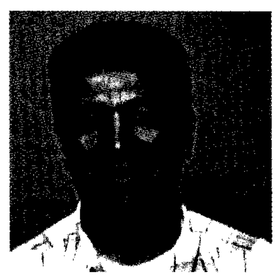

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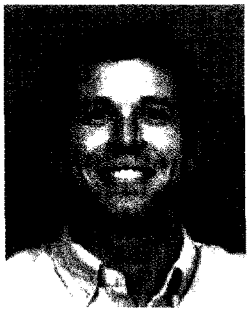

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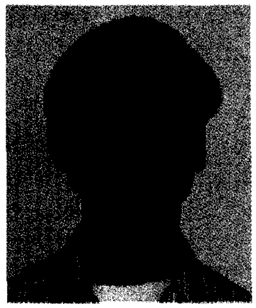

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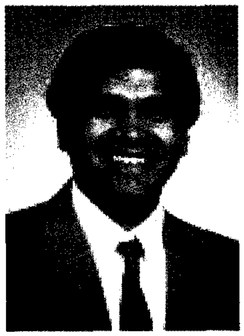

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